

CP Violation in the Lepton Sector:

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Outline:

- Leptonic CP Violation & Cosmology:
- Highlights of Neutrino Oscillations:
- “The Key” - $\nu_\mu \rightarrow \nu_e$:
 - Theory:
 - Experiment: JHF, NuMI, ...
- Summary

Leptonic CP Violation & Cosmology:

- Fukugita and Yanagida -
Phys. Lett. B174, 45 (1986)

- Frampton, Glashow and Yanagida -
[hep-ph/0208157](#)

In a class of models, the sign of the baryon asymmetry is correlate with this leptonic CP violation.

- Endoh, Kaneko, Kang, Morozumi, Tanimoto -
[hep-ph/0209098](#)

Direct link between CP violation in neutrino oscillations and baryogenesis through leptogenesis.

- See also Alejandro Ibarra (Oxford)
“Leptogenesis and Low Energy Phases” in the
Baryogenesis and Phase Transitions parrallel
session.

Baryon Asymmetry is created from a Lepton Asymmetry produced by the decays of heavy Majorana Nu's.

$$\rightarrow \frac{\Gamma(N \rightarrow e^+ \phi^-) - \Gamma(N \rightarrow e^- \phi^+)}{\Gamma(N \rightarrow e^+ \phi^-) + \Gamma(N \rightarrow e^- \phi^+)}$$

$$B_{\text{now}} = \frac{1}{2}(B-L) + \cancel{\frac{1}{2}(B+L)}_0 = \frac{1}{2}(B-L)_{\text{ini}} = -\frac{1}{2}L_{\text{ini}}$$

Related to CP Violation in
Neutrino Oscillations:
Sign & Size

new topics

Leptonic CP and T Violation

CP

$$\nu_\mu \leftrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

T



T

$$\nu_e \leftrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$$

CP

Oscillation Highlights:

With three neutrinos we can access: two δm^2 ,
three mixing angles, θ and one CP or T violating
phase, δ .

(Majorana neutrinos have two more phases inaccessible in oscillations.)

ATMOSPHERIC:

$$|\delta m_{atm}^2| = 3 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} \approx 1.0 \quad \theta_{23} \sim \frac{\pi}{4}$$

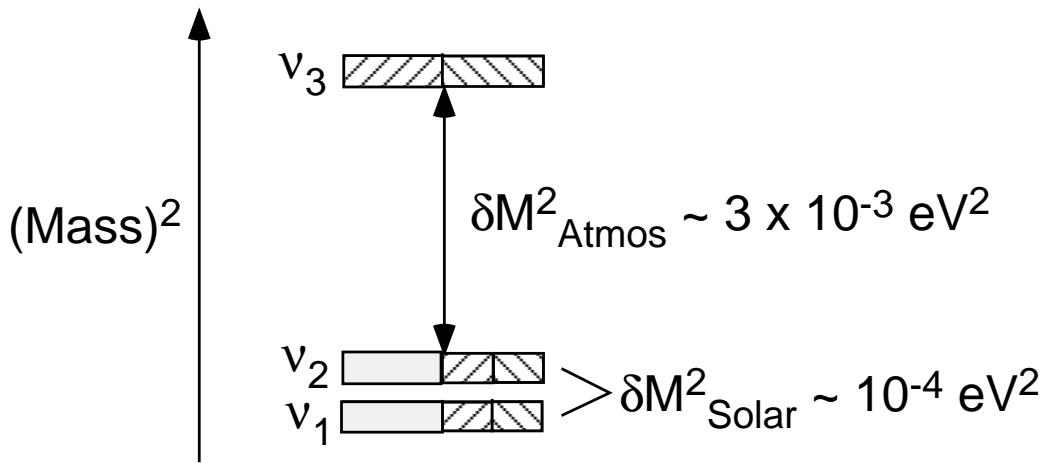
SOLAR: assuming LMA

$$\delta m_{\odot}^2 = +5 \times 10^{-5} eV^2$$

$$\sin^2 2\theta_{12} = 0.8 \quad \theta_{12} \sim \frac{\pi}{6}$$

AND (Chooz)

$$\sin^2 2\theta_{13} < 0.1 \quad \theta_{13} < \frac{\pi}{20}$$



3 active flavors

(but can be easily modified to accommodate 3+1)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

The parameterization used for the unitary MNS matrix, U , is

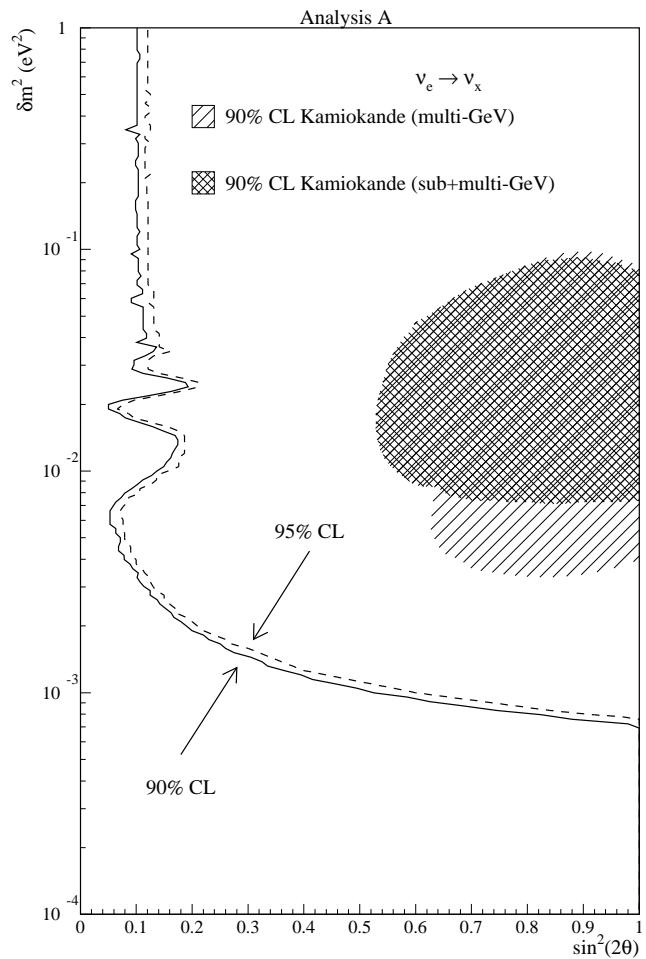
$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & \mathbf{s_{13}e^{-i\delta}} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

where $c_{jk} \equiv \cos \theta_{jk}$ and $s_{jk} \equiv \sin \theta_{jk}$.

The primary element of interest here is

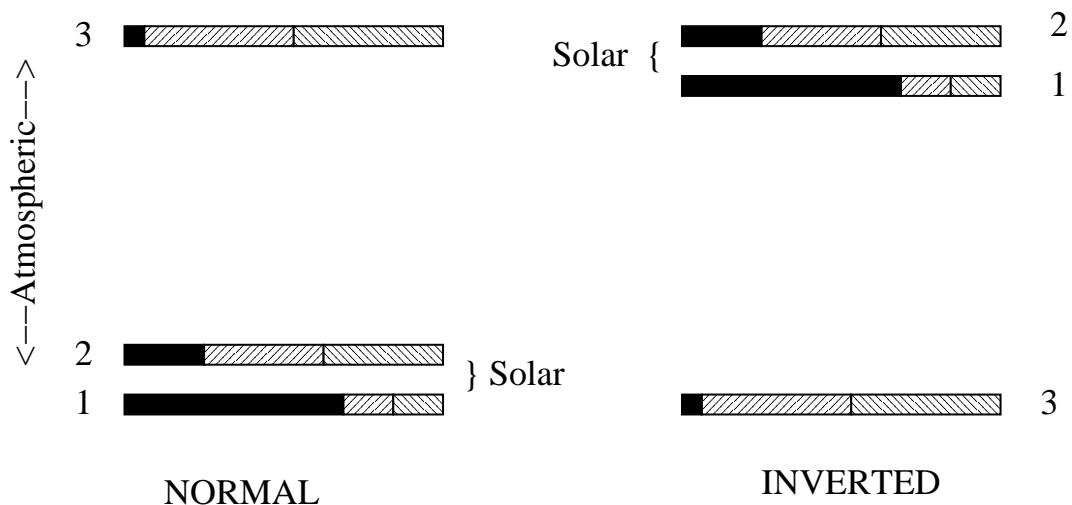
$$U_{e3} \quad \text{or} \quad \sin \theta_{13} e^{-i\delta}.$$

Chooz: ν_e Disappearance



- at $|\delta m_{atm}^2| = 3 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{13} < 0.1$

The Picture:



$$\delta m_{atm}^2 > 0 \quad : \quad \delta m_{atm}^2 < 0$$

- Sign of δm_{atm}^2
 - Size of θ_{13}
 - Value of δ CP Violation!
 - Also value of $\frac{\pi}{4} - \theta_{23}$

“The Key”

$$\nu_\mu \rightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

In vacuum

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta_{atm}) \\ + J_r \Delta_\odot \sin \Delta_{atm} (\cos \delta \cos \Delta_{atm} \pm \sin \delta \sin \Delta_{atm})$$

plus for ν 's and minus for $\bar{\nu}$'s.

$$\Delta_{atm} = \frac{\delta m_{atm}^2 L}{4E} \quad \& \quad \Delta_\odot = \frac{\delta m_\odot^2 L}{4E} \approx \frac{1}{60} \Delta_{atm} \\ (\sim 1.27 \frac{\delta m^2 L}{E} \text{ in } eV^2 km GeV^{-1})$$

with

$$J_r = \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \approx 0.3 \sqrt{\frac{\sin^2 2\theta_{13}}{0.1}}$$

Now the first peak occurs at $\Delta_{atm} = \frac{\pi}{2}$ for

$$E = 1.8 GeV \left(\frac{\delta m_{atm}^2}{3 \times 10^{-3} eV^2} \right) \left(\frac{L}{732 km} \right) \text{ NuMI}$$

$$E = 0.72 GeV \left(\frac{\delta m_{atm}^2}{3 \times 10^{-3} eV^2} \right) \left(\frac{L}{295 km} \right) \text{ JHF}$$

At the first oscillation maximum and using
 $\sin^2 2\theta_{23} = 1$ then

$$P(\nu_\mu \rightarrow \nu_e) = 0.5 \sin^2 2\theta_{13} \pm 0.016 \sin \delta \sin 2\theta_{13}$$

at the upper bound on $\sin^2 2\theta_{13} = 0.1$ (Chooz).

$P(\nu_\mu \rightarrow \nu_e) = 5\% \pm 0.5\% \sin \delta$

- Matter Effects also split
 $\text{Neutrinos from Anti-Neutrinos.}$

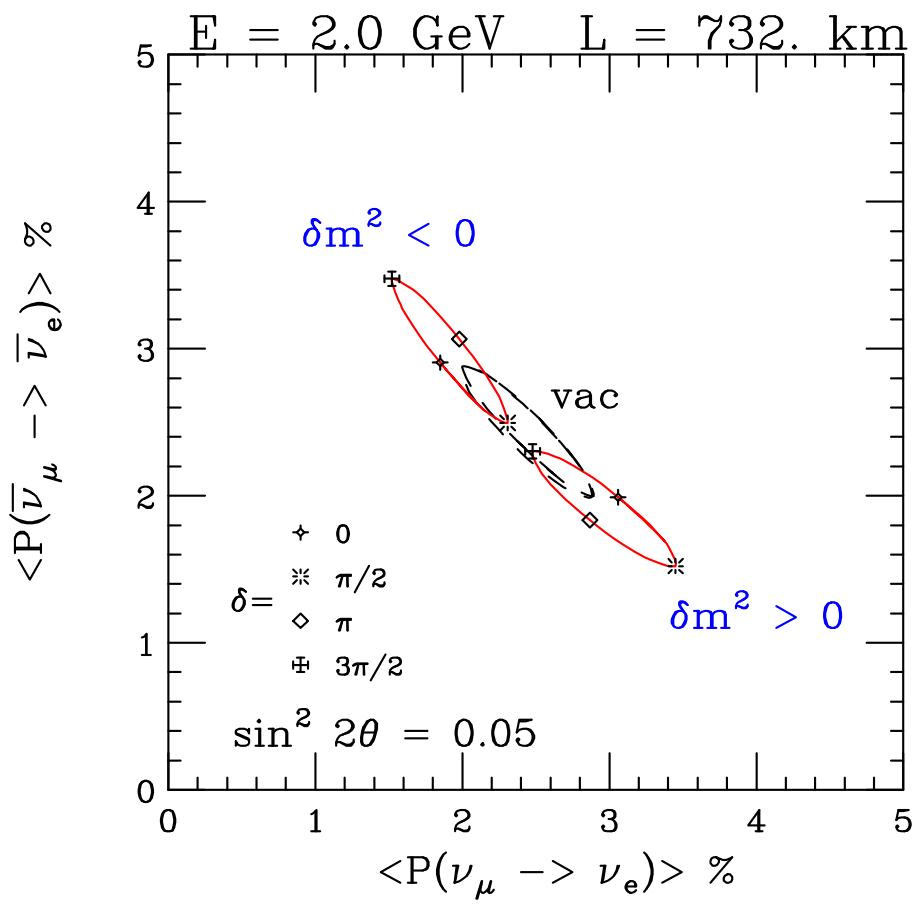
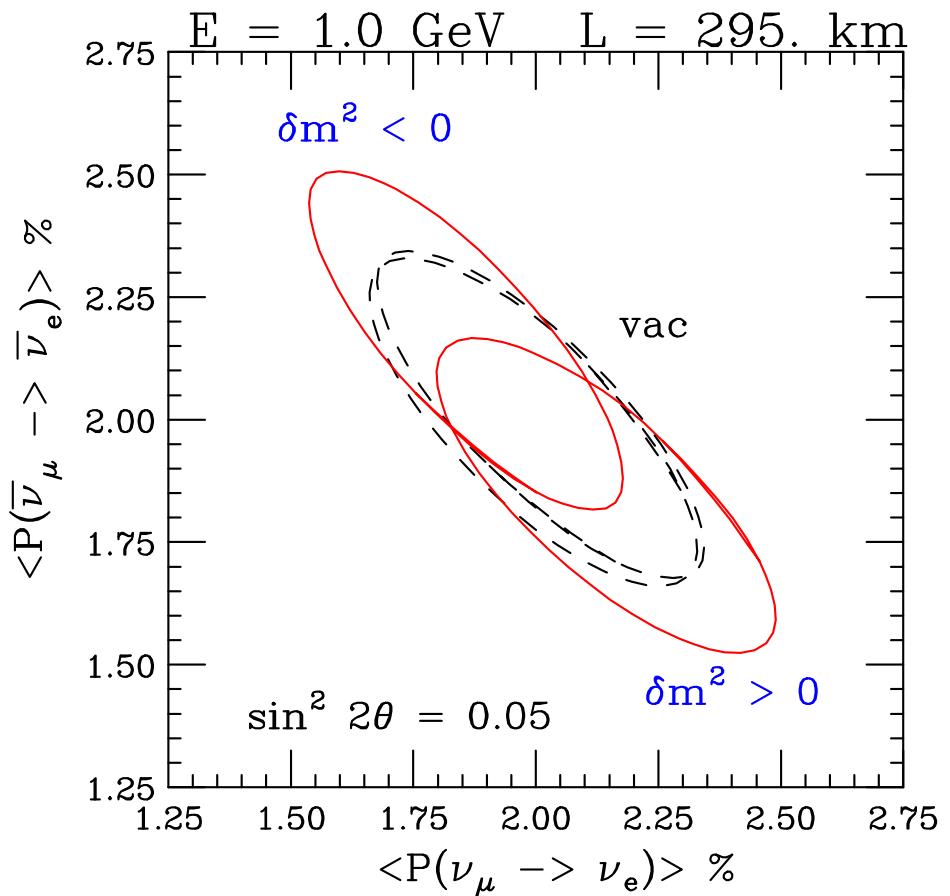
can be used to distinguish

$$\delta m_{atm}^2 > 0 \text{ from } \delta m_{atm}^2 < 0.$$

- Bi-probability Plots

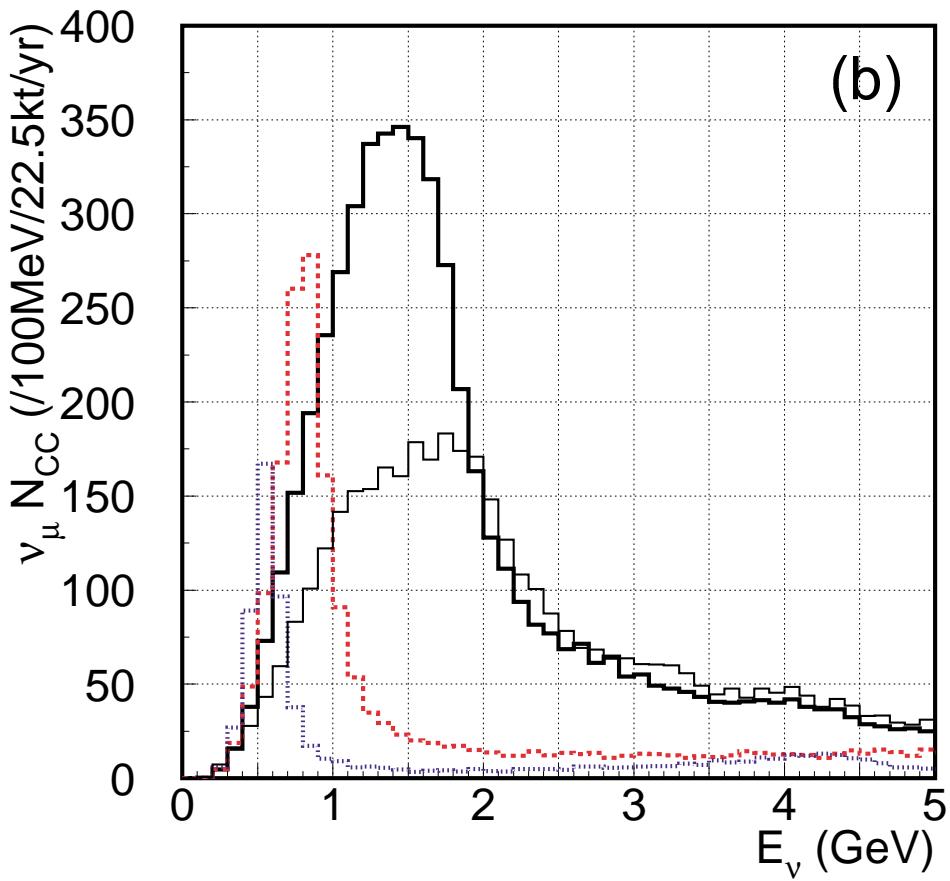
$$P(\nu_\mu \rightarrow \nu_e) \text{ verses } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

holding all parameters fixed except the CP phase,
 δ , which varies from 0 to 2π .



Off Axis Beams

- Higher Intensity at Lower Energy
- Narrower Energy Spread
- Reduction in High Energy Tail



- Just Kinematics !!!
- As angle to beam direction, θ , increases pions of all energies give roughly the same neutrino energy.

$$E_\nu = 0.43E_\pi / (1 + \gamma^2\theta^2) \text{ where } \gamma = E_\pi/M_\pi$$

Near Future Experiments

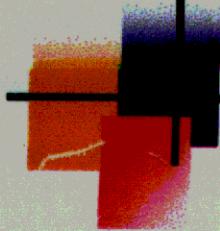
- JHF → Super Kamiokande

See hep-ex/0106019

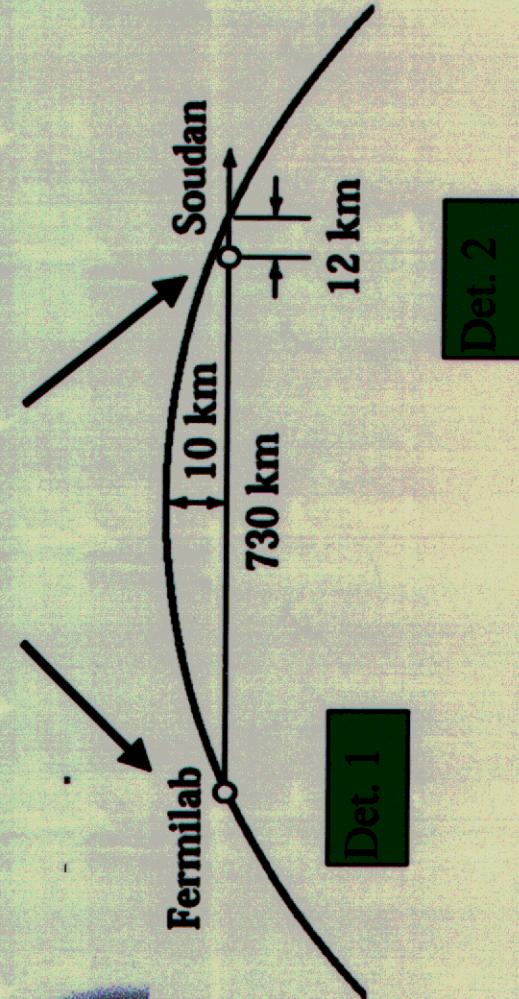
- NuMI → Off Axis Detector

<http://www-off-axiz.fnal.gov/loi>

The NuMI Beamline



Two functionally identical neutrino detectors



<http://www-off-axis.fnal.gov/loi>

JHF → Super-Kamiokande

- 295 km baseline

- Super-Kamiokande:

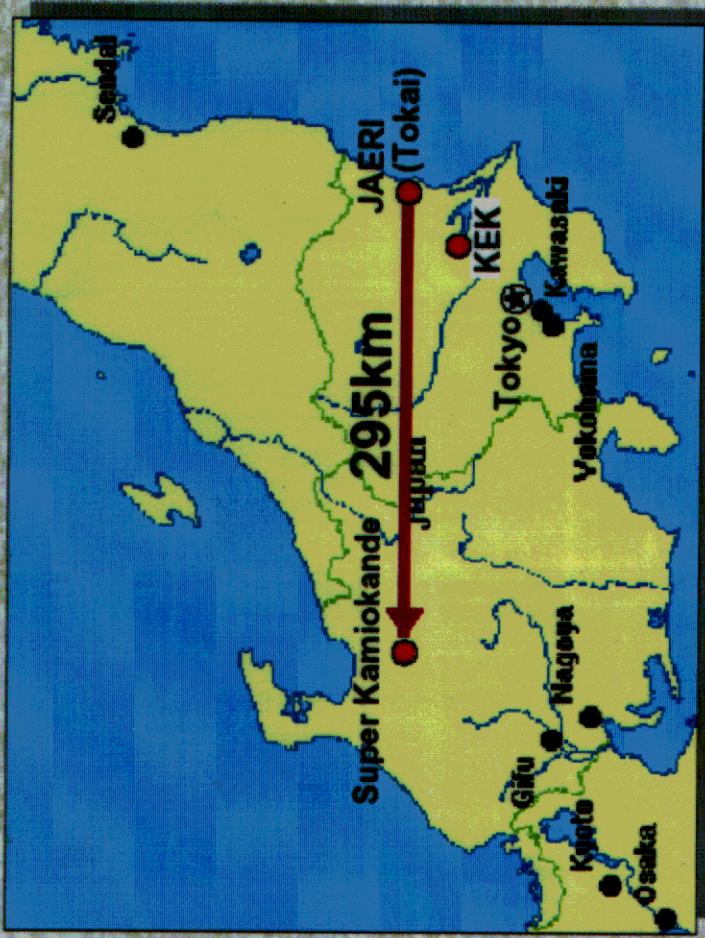
- 22.5 kton fiducial
- Excellent e/ μ ID
- Additional π^0/e ID

- Hyper-Kamiokande

- 20 \times fiducial mass of SuperK

- Matter effects small

- Study using fully simulated and reconstructed data



hep-ex/0106019

SUMMARY:

- If Kamland confirms LMA

and

- θ_{13} is within a factor of 3 of the Chooz bound: ($\sin^2 2\theta_{13} > 0.01$)

then

We have a great OPPORTUNITY!!!

CP Violation in the Lepton Sector is measureable in the near future as well as other neutrinos properties.

- Value of θ_{13} ,
- Normal verses Inverted hierarchy
- Deviation of θ_{23} from $\pi/4$.

and

- CP Violating phase δ .

The full relationship between Leptonic CP Violation and Cosmology especially the lepton and baryon asymmetries is yet to be explored.